Get Real, Get Details, and Get Weather – From Scatterometer

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Introduction

Sailors understand both the importance and the difficulty in getting information on wind over oceans. Just a few decades ago, almost all ocean wind measurements came from merchant ships. The textbooks still describe global ocean wind distribution in sailor's terms: the calms of the Doldrums and Horse Latitudes, the steady Trade Winds, and the ferocity of the Roaring Forties. Today, many citizens believe that operational numerical weather prediction (NWP) will give us all the wind information we need, until a hurricane suddenly intensifies and changes course, or the delay of monsoon brings drought, or the Pacific Trade Wind collapses before an El Nino. When prediction fails and disaster hits, then we remember that NWP depends on models which are limited by our knowledge of the physical processes and the availability of data.

Spaceborne microwave scatterometers are the only proven instruments that will give us real measurements of ocean surface wind vector (both speed and direction) under clear and cloudy conditions, day and night. They give us not only a near-synoptic global view, but details not possible using NWP models. Such coverage and resolution are crucial to understanding and predicting the changes of weather and climate.

Global Coverage and Detailed Structure

All the global wind features of the textbooks displayed in Fig. 1 were produced from one day of observations by the scatterometer on QuikSCAT, clearly demonstrating its capability for global coverage. The North Atlantic is dominated by a high-pressure system, whose anticyclonic (clockwise) flow creates strong winds blowing parallel to the coast of Spain and Morocco, implying strong coastal upwelling in the ocean. Hurricane Floyd, with its high winds (yellow) is clearly visible west of the Bahamas. Tropical depression Gert is forming in the tropical mid-Atlantic (as an anticlockwise spiral) and

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will develop into a full-blown hurricane later. Because the atmosphere is largely transparent to microwaves, QuikSCAT was able to cover 93% of the global oceans, under both clear and cloudy conditions, in a single day.

The coverage of the QuikSCAT makes it the best instrument to provide the synoptic view of the ocean. The high spatial resolution of its data also provides detailed descriptions of small and intense weather systems, like Hurricane Floyd. The insert in Fig. 1, shows that QuikSCAT's 12.5-km spatial resolution allows the delineation of surface wind convergence associated with the multiple rain bands of Hurricane Floyd. The insert also shows that the winds from the Eta model is not even close to being able to resolve such rain bands. Eta is a regional NWP model producing operational wind products with the highest available spatial resolution (40-km). Wind convergence is important because it feeds water vapor to the hurricane; as the water vapor rises, it condenses, releases latent heat, and fuels the hurricane.

On 13 September 1999, Hurricane Floyd turned north. Its strength and proximity to the Atlantic coast caused the largest evacuation of citizens in U.S. history. Landfall of Hurricane Floyd three days later resulted in severe flooding and devastation in the Carolinas. The National Hurricane Center had declared Floyd as a tropical depression on 7 September 1999. Two days earlier, QuikSCAT had already revealed the surface vortex (close circulation) with wind speed meeting the criterion of tropical depression (Fig. 2). QuikSCAT data were available to track the surface vortex all the way back to 2 September 1999 near the African coast. Because such vortices, in their early stages, are too small to be resolved by operational NWP and have no clear cloud signal, the scatterometer, with its high spatial resolution, is the best mean (if not the only mean) of early detection of hurricanes and the study of their genesis.

The subtropical Pacific should be monotonous. The Trade Winds blow steadily from east to west, and so flows the North Equatorial Current. Only the Hawaii Islands break this steady flow. According to conventional theories and observations, the wind wakes caused by the islands should dissipate within 300 km downstream, and should not be felt in the western Pacific. By sacrificing temporal resolution for high spatial sampling, the wind wake, consisting of low winds behind the islands and the strong winds through the gaps, are clearly visible in QuikSCAT data, within 200 km west of the islands (Fig. 3). The fine resolution of QuikSCAT also reveals a persistent wind pattern to the west, composed of alternate high and low winds streaks, and lines of positive and negative curl of wind stress. This pattern stretches a few thousand kilometers from the western side of the Hawaii Islands to beyond Wake Island in the western Pacific. The operational global NWP products (100-km spatial resolution) cannot resolve the mechanical wakes around

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the Hawaii Islands, and the 'long wake' far to the west has never been clearly identified in NWP winds. Wind stress curl usually creates higher and lower sea levels and geostrophic currents.

The altimeter of Topex/Poseidon shows bands of positive and negative sea level changes, implying cyclonic and anticyclonic current gyres with an eastward geostrophic current between them at 19°N; the current should be continuous from western Pacific to the Hawaiian Islands. TMI data reveal a narrow band of warmer water and enhanced atmospheric convection (high cloud water) at the position of the geostrophic current, probably resulted from heat advection from the west. QuikSCAT also observes surface wind convergence and vorticity associated with the warm water and convection. The 'long wake" revealed by QuikSCAT may be sustained by positive feedback between the ocean and the atmosphere. This narrow gap amidst westward flowing wind and current that may have aided the ancient eastward migration of Polynesian across half of the Pacific has never been viewed a single system until now.

The deficiencies of NWP models (caused by lack of knowledge and data) are most evident in the remote oceans around Antarctica. Here, spacebased wind measurements would have the strongest impact. QuikSCAT reveals three groups of intense storms surrounding Antarctica, which are associated with three maxima of sea ice extent (SIE) in Fig. 4. The QuikSCAT observations support the earlier postulation of positive feedback between wind pattern and the SIE maxima, and the SIE maxima provide favorable conditions for cyclogenesis in the open ocean. The wind-ice coupling appears to be most prominent during the La Nina episodes (1996 and 1999) covered by NSCAT and QuikSCAT, and during Austral winters. The figure also demonstrates the capability of scatterometers in monitoring not only ocean surface winds, but also sea ice characteristics and extent.

Scatterometer Missions

The principles of scatterometry have been described in many publications. A summary is given at http://airsea-www.jpl.nasa.gov/scatterometer.html. The past decade has seen continuous improvement to the coverage and resolution of ocean surface winds.

A C-band (5.3 GHz) scatterometer was launched on the first European Remote Sensing (ERS-1) Satellite in 1991, and it was followed by an identical instrument on the ERS-2 launched in 1996. The ERS scatterometers scan a 500-km swath on one side of the

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satellite, providing winds over only 49% of the global ocean daily. The backscatters have 50-km spatial resolution but are sampled at 25 km.

NSCAT, the NASA Ku-band (13.9 GH) scatterometer, was launched in 1996 on the Japanese spacecraft Midori. The six fan-beam antennas provide 600-km swaths on both sides of the spacecraft, covering 73% of global ocean at 25-km resolution daily. The unexpected destruction of the solar array caused the early demise of NSCAT, after returning 9 months of data.

NASA launched QuikSCAT, a Ku-band scatterometer with new design, in 1999. It uses pencil-beam antennas in a conical scan and has a continuous 1,800-km swath that covers 93% of the global ocean in a single day. The standard wind product has 25-km spatial resolution, but special products with 12.5-km resolution for selected regions have been produced. The superior coverage offered by QuikSCAT over previous scatterometers is obvious in Fig 5. Uniformly gridded wind vectors from all these scatterometers can be accessed on line through http://airsea-www.jpl.nasa.gov/seaflux.

Scientific Requirements and Future Perspectives

Large improvement has been made with the four scatterometers launched in the past decade, but continuous effort is still needed to meet the scientific requirements. The time-scales of the initial period in the mid-latitude oceans and diurnal changes in tropical oceans set the highest frequency requirements for measuring ocean surface wind. Record length requirements are set by the importance of continuous and consistent records over the life cycles of climate anomalies, from interannual to decadal. Spatial resolution requirements have been largely driven by the resolution of hurricane structure and coastal ocean upwelling. Even from the vantage point of space, no single polar-orbiting instrument can monitor ocean surface winds with sufficiently high resolution, extensive coverage, and frequent sampling, nor can any single instrument be expected to operate for the long period needed to acquire climate-relevant time series.

More than a single polar-orbiting, wide-swath, scatterometer flying in tandem are needed to meet the frequency requirement. A scatterometer, identical to QuikSCAT, is scheduled to be launched in February 2002, on the Japanese spacecraft ADEOS-2. If there is sufficient overlap between the operations of the two identical scatterometers, the importance of high-frequency wind forcing on the ocean can be demonstrated. The European Space Agency is planning to launch a series C-band dual-swath advanced scatterometers (ASCAT), on their Operational Polar Meteorological Platform (METOP),

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starting in December 2005. It is crucial that the U.S. maintains the wide-swath scatterometers after ADEOS-2 for continuous monitoring of high-frequency ocean surface winds. A sensible way should be sought to move spacebased scatterometer from research to operational agencies, while preserving the continuity and quality of a long data record.

All wind retrieval from past and present scatterometers suffers, at various degrees, ambiguities in wind direction because of the sinusoidal relationship between the backscatter and wind direction. To mitigate the problem, radar measurements of the same area are made in different azimuth angles (angles between the wind and radar beam). Although QuikSCAT has a continuous scan, the azimuth angles are too close together at the outer swath and too far apart near nadir, hampering selection of correct wind direction. Wind fields from operational NWP have usually been used as initial field for the iterative direction-choosing procedures (nudging). The dependence of retrieved wind directional error on the nudging fields (however unlikely) has yet to be vigorously examined. Rain drops in the atmosphere cause attenuation of backscatter return, and they also distort the ocean surface. Due the insufficient validation data, the relation between backscatter and wind vector under heavy precipitation is less well established.

Slight modification of the QuikSCAT instrument to receive cross-polarized backscatter, in addition to co-polarized ones will provide polarimetric capability that theoretically will eliminate the directional ambiguitiy problem. Wind vectors can then be retrieved with uniform accuracy across the swath independent of nudging wind field. Polarimetric scatterometry has the potential of separating the rain effect in the atmosphere from that at the ocean surface, allowing improved wind retrieval under rainy condition. It also does not require full circular scan and may ease the accommodation requirement on operational spacecraft. Resources are needed to test the concept of polarimetric scatterometry.

While we strive to preserve the continuity of wind vector measurements, infusion of new technology is clearly needed to improve the measurements for extended applications and for easier accommodation on operational spacecraft. The scientific need and technology to provide sufficient measurements of ocean surface winds have been demonstrated, but inter-agency and international cooperation still have to be nurtured, and programmatic acumen and political will still must be nourished for success.

Acknowledgment

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Figure Legends

Fig. 1 White streamlines indicating wind direction are superimposed on the color image of wind speed, derived from objective interpolation of the observations by QuikSCAT. Normalized backscatter coefficients measured by the same instrument over land and Antarctica are also added. In the inserted figures, black arrows representing wind vectors are superimposed on the color image of wind convergence, derived from QuikSCAT (upper) and from Eta model (lower).
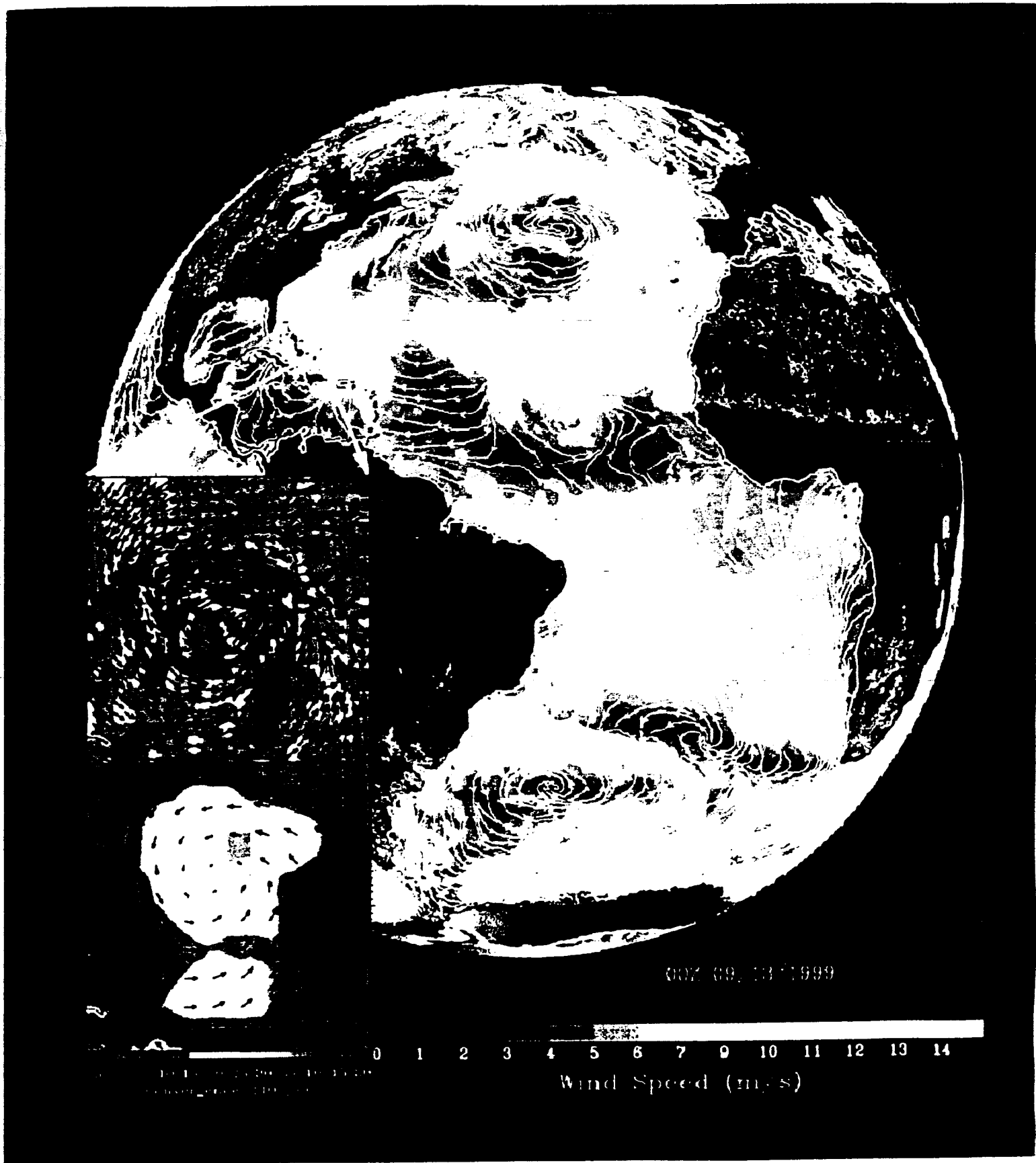
Fig. 2 Track of Hurricane Floyd issued by the National Hurricane Center and revealed by QuikSCAT.

Fig. 3 Wind speed, meridional wind component, and wind vector superimposed on curl of wind stress derived from the first five months of QuikSCAT observations are shown with the sea level and geostrophic current changes derived from Topex/Poseidon observations over the same period. The meridional running-mean representing the large scale gradient have been removed from the data.
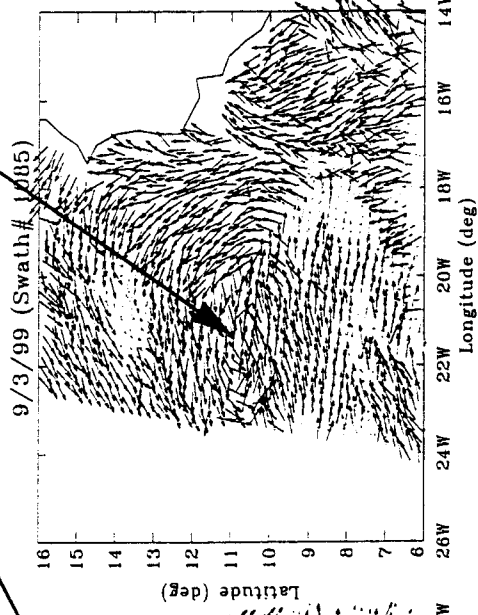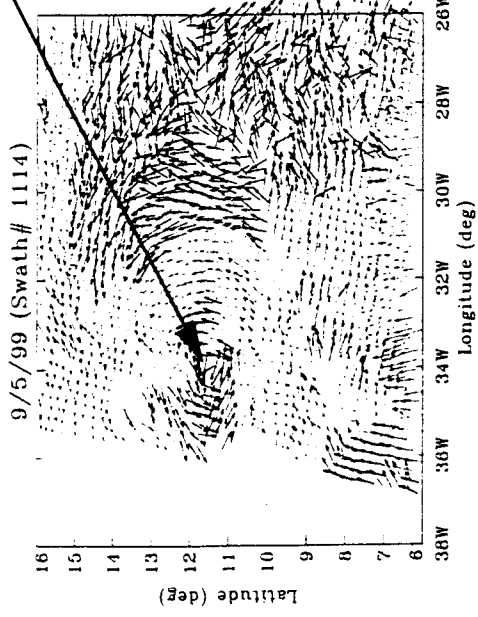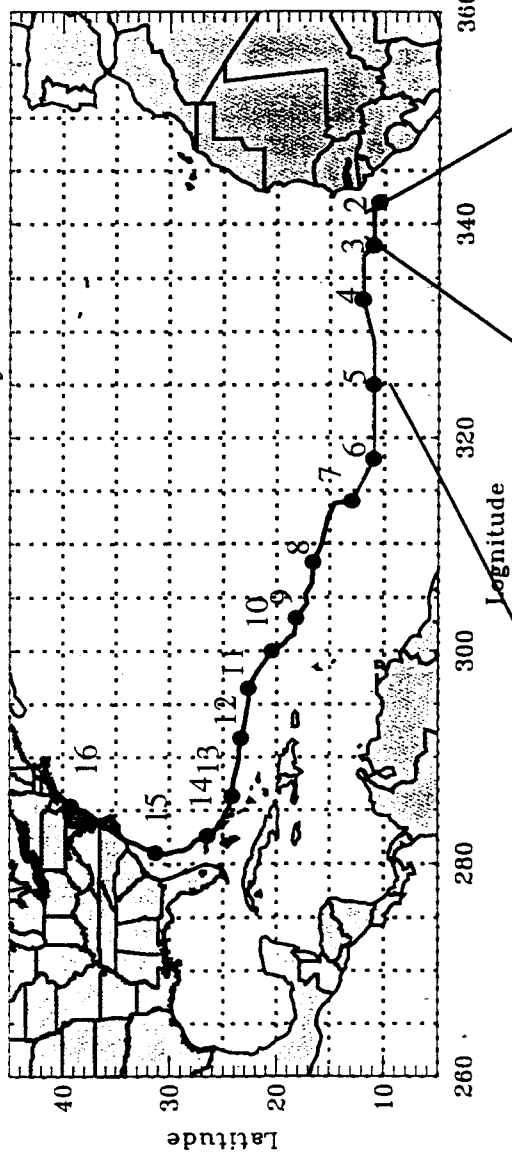
Fig. 4 The gray-scale image shows various kinds of ice in Antarctica. The landmass is outlined by the white-line. The gray area outside the landmass is occupied by sea ice. Outside of the ice, white streamlines representing wind directions are overlaid onto the color image of wind speed distribution. The map (including both ice and wind) was produced from one day of QuikSCAT observations.

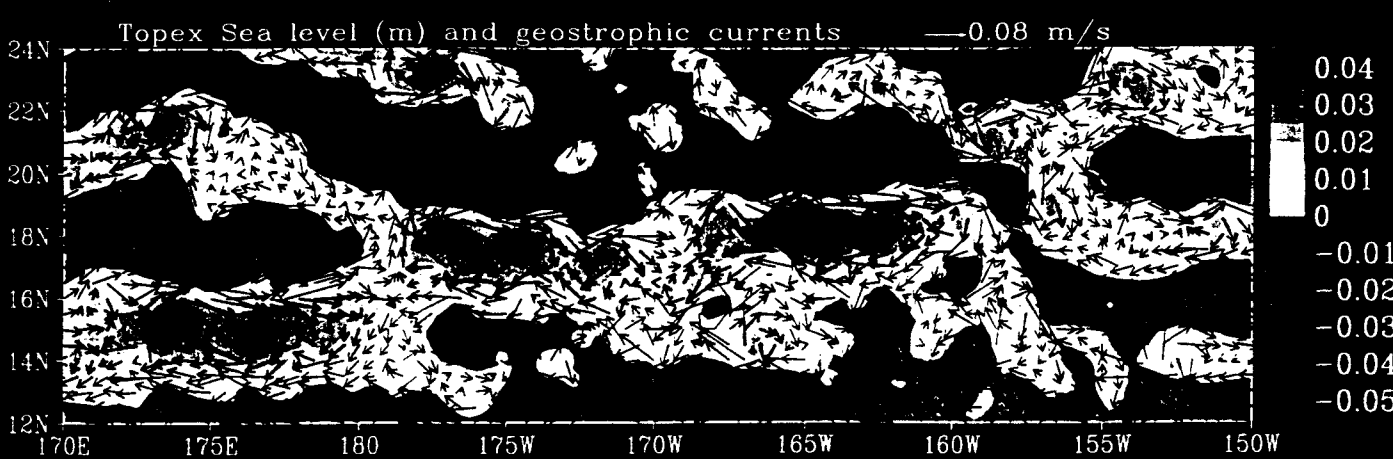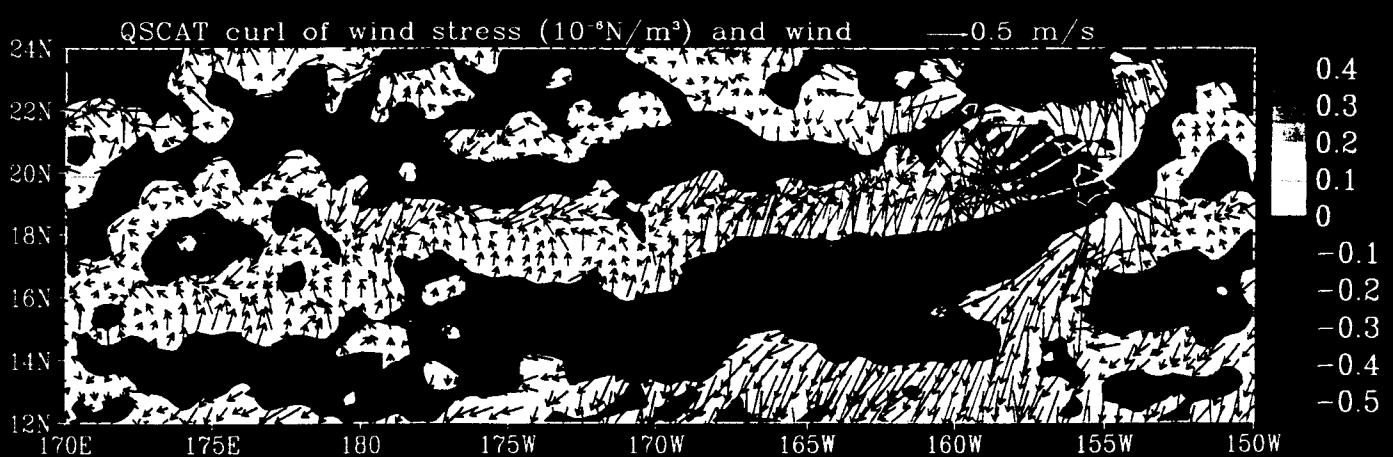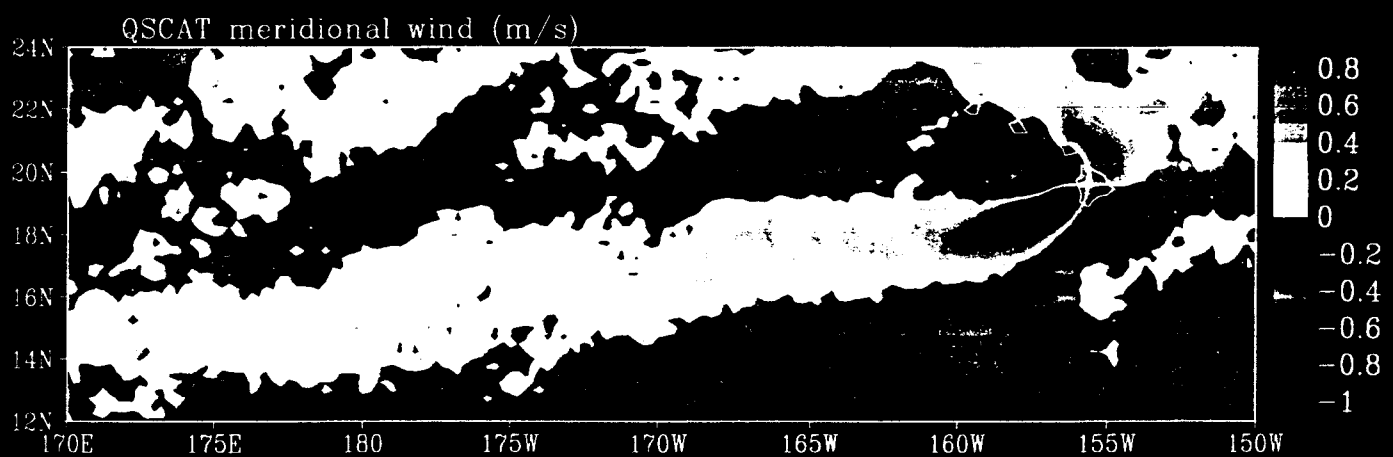Fig. 5 Typical daily coverage by the scatterometer on ERS-2 (upper), NSCAT (center) and QuikSCAT (lower).
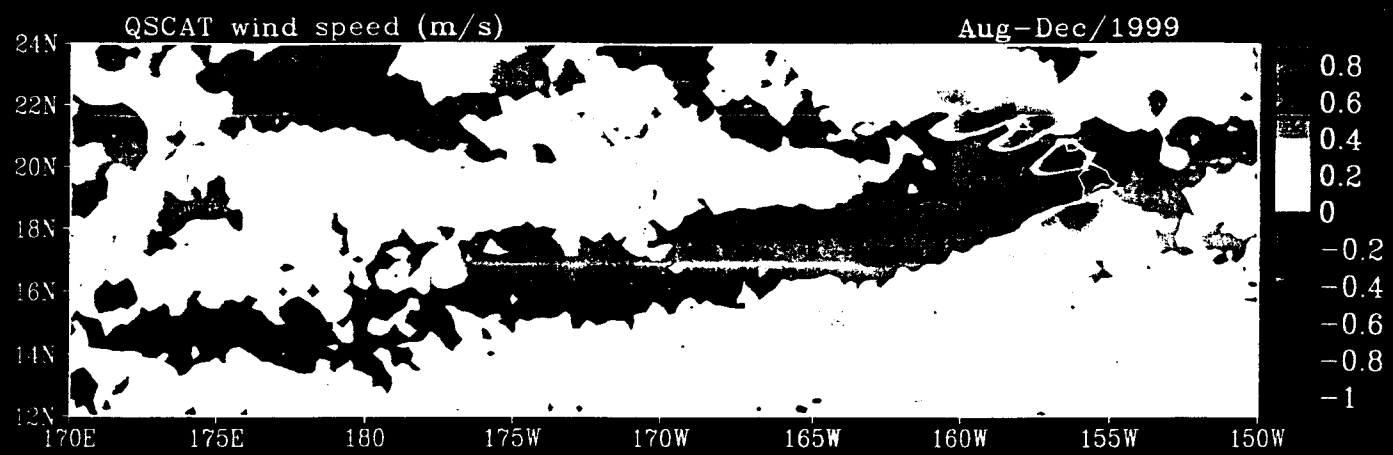
Photograph: QuikSCAT being assembled at Ball Aerospace

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OCT 09, 13 1999

Wind Speed (m/s)

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

Track of Hurricane Floyd

NHC

Quik SCAT

9/2/99 (Swath # 1071)

9/3/99 (Swath # 1085)

9/5/99 (Swath # 1114)

QSCAT wind speed (m/s)   Aug–Dec/1999

QSCAT meridional wind (m/s)

QSCAT curl of wind stress ($10^{-8}N/m^3$) and wind   →0.5 m/s

Topex Sea level (m) and geostrophic currents   →0.08 m/s
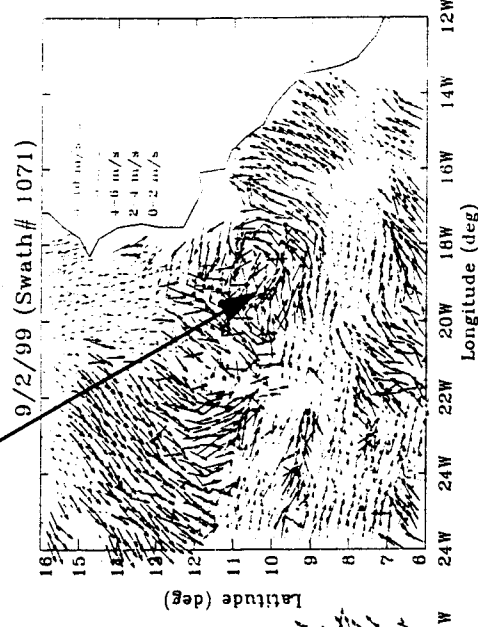
09Z, 07/21/1999

Wind Speed (m/s)

Wind Speed U (m/s): $0 \le U < 5$ $5 \le U < 10$